

Geometry of the vertebral bodies and the intervertebral discs in lumbar segments adjacent to spondylolysis and spondylolisthesis: pilot study

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Abstract The objective is to evaluate the geometric parameters of vertebral bodies and intervertebral discs in spinal segments adjacent to spondylolysis and spondylolisthesis. This pilot cross-sectional study was an ancillary project to the Framingham Heart Study. The presence of spondylolysis and spondylolisthesis as well as measurements of spinal geometry were identified on CT imaging of 188 individuals. Spinal geometry measurements included lordosis angle, wedging of each lumbar vertebra and intervertebral disc. Last measurements were used to calculate ΣB , the sum of the lumbar L1–L5 body wedge angles; and ΣD , the sum of the lumbar L1–L5 intervertebral disc angles. Using Wilcoxon–Mann–Whitney test we compared the geometric parameters between individuals with no pathology and ones with spondylolysis (with no listhesis) at L5 vertebra, ones with isthmic spondylolisthesis at L5–S1 level, and ones with degenerative spondylolisthesis at L5–S1 level. Spinal geometry in individuals with spondylolysis or listhesis at L5 shows three major

patterns: In spondylolysis without listhesis, spinal morphology is similar to that of healthy individuals; In isthmic spondylolisthesis there is high lordosis angle, high L5 vertebral body wedging and very high L4–5 disc wedging; In degenerative spondylolisthesis, spinal morphology shows more lordotic wedging of the L5 vertebral body, and less lordotic wedging of intervertebral discs. In conclusion, there are unique geometrical features of the vertebrae and discs in spondylolysis or listhesis. These findings need to be reproduced in larger scale study.

Keywords Spondylolysis · Isthmic spondylolisthesis · Degenerative spondylolisthesis · Spine · Intervertebral disc · Vertebral body

Introduction

The analysis of the sagittal balance of the spine recently appeared to be essential in the management of lumbar degenerative pathologies, especially when a spinal fusion is achieved like in advanced spondylolisthesis [1, 2]. The sagittal balance is characterized by both pelvic and spinal parameters. Patients with spondylolysis and spondylolisthesis demonstrated a significantly greater pelvic incidence than the normal population [3]; sacral tilt is high in patients with spondylolysis and low grades of isthmic spondylolisthesis (grade 1 or 2 according to the Meyerding [4] classification) and low in severe isthmic spondylolisthesis (grade 3 or 4 according to the Meyerding [4] classification) [5]. Lumbar spines with spondylolysis and spondylolisthesis usually demonstrate high lumbar lordosis, high lumbosacral angle and high inclination of superior and inferior endplate of the last lumbar vertebra (L5) in relation to the horizon [6, 7].

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Several studies have analyzed the lumbar index (that reflects the degree of wedge deformity of the vertebral body) of the slipped vertebra in spondylolisthesis. Most studies found a lower lumbar index in spondylolysis patients (more lordotic wedging of the vertebral bodies) [8–10]. The wedging of the intervertebral disc below the slipped vertebra has been shown to have diagnostic relevance in individuals with degenerative spondylolisthesis as well as implications to the pathogenesis of disability [7, 11].

While pelvic and lumbar parameters, as well as specific parameters of the affected vertebra have been extensively studied in spondylolysis and spondylolisthesis, there is very little data available regarding the geometry of the lumbar segments adjacent to the affected vertebra. As the spine keeps global sagittal spino-pelvic alignment [6], we have reason to assume that this equilibrium is achieved by the wedging of the spinal segments adjacent to the affected segment, amongst other parameters. The knowledge of geometrical parameters of vertebral bodies and intervertebral discs adjacent to the segment with spondylolysis or spondylolisthesis can help to understand the etiology of these spinal disorders and can be potentially important for early diagnosis, prevention and treatment of these conditions.

The aim of this pilot study was to evaluate the wedging of vertebral bodies and intervertebral discs in the affected segment as well as the spinal segments adjacent to spondylolysis and isthmic and degenerative spondylolisthesis in the last lumbar vertebra (L5).

Methods

Study design

Cross-sectional pilot study that was an ancillary project to the Framingham Heart Study.

Sample

The Framingham Heart Study began in 1948. Initially, 5,209 men and women between the ages of 30 and 60 years living in Framingham, Massachusetts were enrolled. In 1971, 5,124 offspring (and their spouses) of the original cohort were entered into the offspring cohort. In 2002, 4,095 men and women who were children of the offspring cohort were enrolled in the third generation cohort [12, 13]. 3,529 participants of the Framingham study (from the offspring and third generation cohorts) aged 40–80 years underwent abdominal and chest multi-detector CT scanning to assess coronary and aortic calcification. During the CT study, 188 participants were consecutively enrolled in

this ancillary study to assess the association between CT-observed characteristics of the lumbosacral spine and back pain. The results of this study were previously reported [14, 15].

Imaging parameters

Study participants were imaged with an eight-slice multi-detector CT scanner (Lightspeed Ultra, GE, Milwaukee, WI, USA). Each subject underwent unenhanced abdominal multi-detector CT in a supine position using a sequential scan protocol with a slice collimation of 8×2.5 mm (120 KVp, 320/400 mA for 220 lbs body weight, respectively) during a single end-inspiratory breath hold. For the abdominal scan, thirty contiguous 5-mm thick slices of the abdomen were acquired covering 150 mm above the level of S1.

The evaluation of all spinal degeneration parameters in this study was performed using eFilm Workstation (Version 2.0.0) software.

Spondylolysis and spondylolisthesis evaluation

CT scans were evaluated in blinded fashion with respect to clinical and personal data. The entire lumbar spine was reviewed for each case, using bone windows. Both axial views and multiplanar reconstruction were analyzed. On CT scan, spondylolysis is well demonstrated as a linear lucidity or defect extending through the pars interarticularis. Spondylolysis was marked as present or absent at right or left sides of the lumbar vertebrae or bilateral. In the case where the image review was equivocal, it was evaluated again by two readers. CT evaluation of spondylolysis and spondylolisthesis, especially using multiplanar reconstruction has previously been described as a reliable and accurate method [16, 17]. Any clearly detectable anterolisthesis was considered as spondylolisthesis. Spondylolisthesis identified at a spinal segment with bilateral spondylolysis was considered isthmic spondylolisthesis. Spondylolisthesis observed in the absence of spondylolysis was considered degenerative spondylolisthesis. There were no individuals with spondylolisthesis associated with unilateral spondylolysis in the studied sample.

Vertebral body and intervertebral disc geometry evaluation

For evaluation of spinal geometrical parameters, sagittal reconstructions were used. For a detailed description of the vertebral body and intervertebral disc geometry evaluation, as well as rationalization of this measurements, please see Vialle et al. [5], Been et al. [18], De Carvalho [19] and Kimura et al. [20]. For each of the five lumbar vertebrae,

two lines were drawn: along the superior endplate of the vertebral body (also on the first sacral vertebra) and along the inferior endplate of the vertebral body (Fig. 1). These lines were used to measure four angles: the lordosis angle (LA) between the superior endplate of L1 and the superior endplate of S1; the body wedge angle (B) between the superior and inferior endplates of a single vertebra and the intervertebral disc angle (D) between the inferior endplate of one vertebra and the superior endplate of the successive vertebra (Fig. 1). Measurements B and D were taken for each of the five lumbar segments. Measurements B and D were used to calculate ΣB , the sum of the lumbar L1–L5 body wedge angles; and ΣD , the sum of the lumbar L1–L5 intervertebral disc angles.

Reliability of CT readings

An initial set of CTs were analyzed to develop a reading protocol for evaluation of spondylolysis and spondylolisthesis. Using this protocol, the intra- and inter-rater reliability was calculated for two readers. All CT scans were then analyzed in blinded fashion. Before analyzing each new set of CT scans, five previously analyzed CTs were reevaluated to “recalibrate” the readings to a standard. The intra-observer reliability for identification of spondylolysis was 1.00. The inter-observer reliability was 0.98. For spondylolisthesis, the intra-observer reliability varied at different levels between 0.95 and 1.00, and the inter-observer reliability ranged from 0.75 to 0.98.

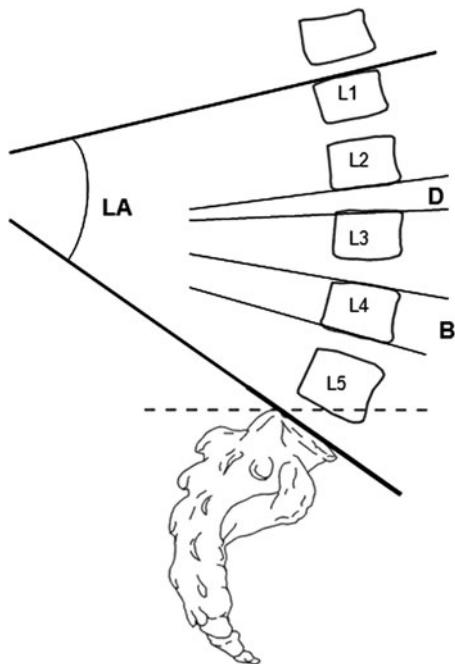


Fig. 1 Schema of measurements of geometrical parameters of lumbar spine

All measurements of spinal geometry were taken by the one investigator (EB), blinded to patient identifiers, using eFilm Workstation (Version 2.0.0) software. To evaluate the intra-rater reliability, 30 CT scans were evaluated twice. The intra-observer reliability (kappa statistics) for measurements of LA was 0.93, for B measurements ranged from 0.80 to 0.95 and for D measurements ranged from 0.85 to 0.96. This range of kappa statistics represents good to excellent reproducibility.

Statistical analysis

First, we calculated the mean age ($\pm SD$) of individuals with no lysis or listhesis, with spondylolysis with no listhesis, with isthmic spondylolisthesis and with degenerative spondylolisthesis. Second, we calculated the mean values ($\pm SD$) of vertebral body wedging (B) of L3, L4 and L5 vertebrae, intervertebral disc wedging (D) of L3–4, L4–5L and L5–S1 discs, as well as ΣB , ΣD and LA in individuals without spondylolysis or spondylolisthesis at any lumbar spinal level. Third, we calculated the same parameters in individuals with spondylolysis (with no listhesis) at L5 vertebra; in individuals with isthmic spondylolisthesis at L5–S1 level; and in individuals with degenerative spondylolisthesis at L5–S1 level. Forth, we compared all measured parameters in normal individuals with ones in groups of individuals with aforementioned lumbar pathologies using Wilcoxon–Mann–Whitney test. This test was chosen, because of relatively small sample size of individuals with studied pathologies and severe imbalance between the groups with and without spinal pathology.

Results

Out of the 188 participants, 121 had no spondylolysis or spondylolisthesis at any level. 16 had spondylolysis at L5 (9%), out of which 11 had isthmic spondylolisthesis at L5–S1 (6%), and five had lysis without listhesis (3%). There were 10 individuals with degenerative spondylolisthesis at L5–S1 (5%). To simplify the understanding of geometrical deviations in spinal segments with spondylolysis and spondylolisthesis, we decided to concentrate on one spinal level with the highest number of studied pathology (L5 for lysis and L5–S1 for listhesis). Therefore, we excluded from the study seven individuals with degenerative spondylolisthesis and two with isthmic spondylolisthesis at L4–L5 level, three individuals with degenerative spondylolisthesis at L3–L4, and four with spondylolysis at L4, and one with spondylolysis at L3 level. Another 29 individuals, all without spondylolysis or spondylolisthesis in the lumbar area were not included in the analysis due to difficulty in performing precise measurements of vertebral bodies and intervertebral

disc wedging, mostly due to poor axial reconstruction. Overall, 142 individuals were analyzed. There were no significant differences in demographic parameters between not-included and analyzed sub-samples.

The mean age (SD) of individuals with no spondylolysis or spondylolisthesis ("normal") was 50.72 (10.53). The age of individuals with isthmic spondylolisthesis was 52.82 (12.53), that was not different from age of "normal" individuals ($p = 0.531$). The age of individuals with degenerative spondylolisthesis was significantly higher than "normal" ones [58.18 (6.93), $p = 0.022$]. The highest mean age was found in group of individuals with spondylolysis, but without listhesis [62.67 (3.39), $p = 0.006$].

The lordosis angle, of the individuals with no spinal pathology was 45.9 ± 9.9 degrees. All three groups showed higher LAs than healthy individuals: 52.4 ± 9.2 for individuals with spondylolysis without listhesis; 52.6 ± 15.4 for individuals with degenerative spondylolisthesis and 53.8 ± 7.3 for individuals with isthmic spondylolisthesis, but the difference is significant only in the latter ($p = 0.01$) (Table 1).

The sum of vertebral bodies' angles, ΣB of the individuals with no spinal pathology was 3.6 ± 10.2 . Individuals with spondylolysis (with or without listhesis) showed slightly higher wedging of their vertebral bodies (6.3 ± 8.1 , $p = 0.622$; 8.6 ± 11.7 , $p = 0.298$, respectively), but the difference was not significant. Individuals with degenerative spondylolisthesis showed significantly more lordotic wedging of their vertebral bodies (13.5 ± 11.7 , $p = 0.032$) than individuals with no spinal pathology.

The sum of intervertebral discs angles, ΣD angle of the individuals with no spinal pathology was 40.9 ± 10.2 . Individuals with lysis without listhesis showed comparable

ΣD angles to individuals with no spinal pathology: 40.6 ± 10.4 ($p = 0.891$), individuals with isthmic spondylolisthesis showed somewhat higher ΣD angle 47.0 ± 8.7 ($p = 0.101$), and individuals with degenerative spondylolisthesis showed comparable ΣD angles to individuals with no spinal pathology: 38.1 ± 8.9 , $p = 0.657$.

The vertebral bodies (B) of individuals with no spinal pathology showed no wedging—square vertebral body—at L3 (0.5 ± 2.9), and lordotic wedging at L4 and L5 (2.6 ± 2.8 , 8.4 ± 3.5 , respectively). The vertebral bodies of individuals with spondylolysis without listhesis show slightly kyphotic wedging at L3, and lordotic wedging at L4 and L5. Individuals with isthmic spondylolisthesis showed comparable wedging of their vertebral bodies to the individuals with no spinal pathology at L3–L4 (-0.1 ± 2.2 , 2.9 ± 3.4 , respectively), but significantly higher LA compared to the individuals with no spinal pathology at L5 (12.3 ± 4.7 , $p = 0.020$). Individuals with degenerative spondylolisthesis showed more lordotic wedging of their vertebral bodies at all spinal levels L3–L5 (0.8 ± 3.4 , 5.4 ± 4.1 , 11.1 ± 2.4 , respectively), but the difference was only significant at L5 ($p = 0.031$) (see Table 1; Fig. 2).

The wedging of the intervertebral discs (D) of individuals with no spinal pathology showed a gradient increase from the L2–3 (5.5 ± 3.3) to the L5–S1 disc (13.2 ± 5.5) (see Table 1; Fig. 3). Individuals with spondylolysis without listhesis showed similar wedging of their intervertebral discs to the normal at all spinal levels. In individuals with isthmic spondylolisthesis the disc above the affected vertebra (L4–5) showed a significant increase of its wedging angle— 14.8 ± 3.3 versus normal (9.8 ± 3.8); whereas at the level of listhesis (L5–S1) the disc showed a slight decrease of its wedging— 11.3 ± 5.8 in isthmic

Table 1 Geometrical parameters of vertebral bodies and intervertebral discs

	Normal ($N = 121$)	Spondylolysis L5 (no listhesis) ($N = 5$)		Isthmic spondylolisthesis L5–S1 ($N = 11$)		Degenerative spondylolisthesis L5–S1 ($N = 10$)	
		Mean \pm SD	Comp. ^a	Mean \pm SD	Comp. ^a	Mean \pm SD	Comp. ^a
LA	45.6 (9.9)	52.4 (9.2)	0.1457	53.8 (7.3)	0.0174	52.6 (15.4)	0.2410
ΣB	3.6 (10.2)	8.6 (11.7)	0.2984	6.3 (8.1)	0.6225	13.5 (11.7)	0.0319
ΣD	40.9 (10.2)	40.6 (10.4)	0.8908	47.0 (8.7)	0.1011	38.1 (8.9)	0.6573
VBW L3	0.5 (2.9)	<i>-1.8 (2.5)</i>	0.0874	<i>-0.1 (2.2)</i>	0.4775	0.8 (3.4)	0.8292
VBW L4	2.6 (2.8)	3.8 (3.7)	0.5895	2.9 (3.4)	0.6985	<i>5.4 (4.1)</i>	0.0888
VBW L5	8.4 (3.5)	10.2 (5.3)	0.3486	12.3 (4.7)	0.0204	11.1 (2.4)	0.0307
IDW L2–3	5.5 (3.3)	6.2 (4.4)	0.8362	6.6 (2.8)	0.2572	7.6 (2.0)	0.0543
IDW L3–4	7.3 (3.2)	8.2 (3.4)	0.4403	7.6 (1.5)	0.6516	8.9 (4.5)	0.1605
IDW L4–5	9.8 (3.8)	9.6 (4.0)	0.9302	14.8 (3.3)	0.0021	8.0 (2.3)	0.1190
IDW L5–S1	13.2 (5.5)	12 (8.8)	0.9801	11.3 (5.8)	0.5947	7.8 (2.8)	0.0028

VBW vertebral body wedging, IDW intervertebral disc wedging, LA lordosis angle, ΣB sum of five lumbar vertebral bodies wedging, ΣD sum of five lumbar intervertebral discs wedging, Comp. comparison with normal spine. **Bold** $p < 0.05$. *Italics* $0.05 < p < 0.10$

^a Wilcoxon–Mann–Whitney test

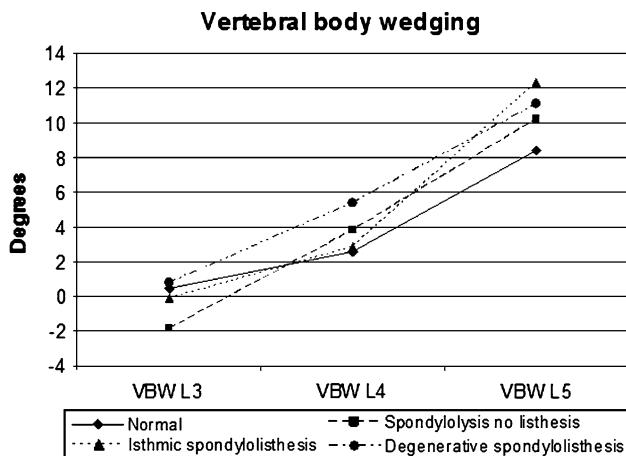


Fig. 2 Vertebral body wedging (VBW) of the lumbar spine in individuals: with normal lower spinal segment, with spondylolysis without listhesis, with isthmic and degenerative spondylolisthesis

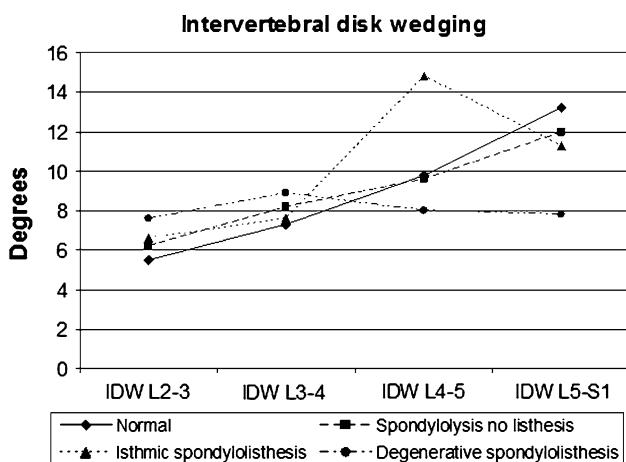


Fig. 3 Intervertebral disk wedging (IDW) of the lumbar spine in individuals: with normal lower spinal segment, with spondylolysis without listhesis, with isthmic and degenerative spondylolisthesis

spondylolisthesis versus normal— 13.2 ± 5.5 . The wedging of the discs in individuals with degenerative spondylolisthesis showed another unique pattern. The wedging of the intervertebral discs is almost constant along the lumbar spine; it is similar at any spinal level ranging from 7.6 ± 2.0 at the L2–3 level to 8.9 ± 4.5 at the L3–4 level. The wedging of the intervertebral discs in individuals with degenerative spondylolisthesis is lacking the gradient increase of the intervertebral disk wedging shown by the individuals with no spinal pathology.

Discussion

There are unique geometrical features of the vertebrae and intervertebral discs adjacent to spinal segments with spondylolysis or listhesis at the lower lumbar spine. First,

spinal morphology of individuals with L5 spondylolysis without listhesis is similar to that of individuals with normal lower spinal segments. Second, individuals with isthmic spondylolisthesis (grades 1 and 2) are characterized by high LAs, high lordotic wedging of the affected vertebra (L5) and very high L4–5 intervertebral disc wedging. The high LA and the excessive wedging at L5 found in patients with isthmic spondylolisthesis confirms previously published data [21]. Third, spinal morphology in individuals with degenerative spondylolisthesis is characterized by high Σ B—the sum of the lumbar L1–L5 body wedge angles, high lordotic wedging of the L5 vertebral body and similarity in the wedging of the intervertebral disks at spinal levels L2–3 to L5–S1. The small wedging of the intervertebral disc below the slipped vertebra as well as the excessive wedging of the L5 vertebral body in degenerative spondylolisthesis has already been shown by several studies [7–11, 22].

There are several limitations of the recent study. First, limitation is the small sample size. The results of this study need to be replicated in different, larger sample. Second, the cross-sectional design of our study is not allowing the evaluation of causal relationships between spinal pathology and geometry. Third, as the CT scans were performed in a supine position, this might have an effect on the wedging of the intervertebral disks. In a recent open-MRI study, the lordosis showed a significant increase of 6.3° (14%) from supine to true standing position [23]. When comparing the LA of the normal individuals to that of other studies that have used lateral standing radiographs, we found that the LA from our study is $2.5\text{--}13^\circ$ smaller than the LA measured on lateral standing radiographs (Table 2) which is in accordance with [23]. Obviously, there is a great similarity in the wedging of the vertebral bodies between the standing radiographs and supine CT measurements. As to the intervertebral disks, the normal individuals from our study (supine position) exhibit smaller intervertebral disk wedging in L2–3, L3–4, and L4–5 when compared with standing radiographs, but the last intervertebral disk L5–S1 shows comparable disk wedging between supine CT and standing radiographs (Table 2). However, all individuals in this study were evaluated at the same position. The differences that were found are accurate for supine position. We suggest that this study needs to be replicated in a larger sample and using lateral standing radiographs.

The major geometrical differences between the lumbar spines of individuals with spondylolysis to that of isthmic spondylolisthesis is in the wedging of the intervertebral discs above the slipped vertebra (intervertebral disc L4–5). While individuals with lysis but without listhesis show disc wedging comparable to healthy individuals, individuals with isthmic listhesis show very high wedging in the L4–5 intervertebral disc. Two scenarios might explain these

Table 2 Comparison of geometrical parameters of the lumbar spine between Supine CT evaluated subjects (current study) and standing, radiographic evaluated subjects

	Current study	Been et al. [18]	Vialle et al. [5]	Chen [27]	De Carvalho [19]
Mode	CT scan	Radiograph	Radiograph	Radiograph	Radiograph
Posture	Supine	Standing	Standing	Standing	Standing
LA	45.6 (9.9)	51.3 (10.7)	58.5	48.1 (11.1)	63 (15)
ΣB	3.6 (10.2)	5.6 (10)	6.2	-1.9	
ΣD	40.9 (10.2)	45.5 (10.3)	52.3	50.0	46.7
VBW L3	0.5 (2.9)	-0.2 (2.6)	0.6	-0.7 (1.3)	
VBW L4	2.6 (2.8)	2.2 (3.2)	2.6	1.8 (4.1)	
VBW L5	8.4 (3.5)	8.2 (3.3)	8.0	7.2 (2.8)	
IDW L2–3	5.5 (3.3)	7.3 (2.6)	8.0	7.6 (4.5)	5.9
IDW L3–4	7.3 (3.2)	9.0 (3.2)	9.4	11.4 (3.4)	8.1
IDW L4–5	9.8 (3.8)	11.2 (3.5)	14.1	13 (4.1)	12.5
IDW L5–S1	13.2 (5.5)	11.7 (4.7)	15.3	13.6 (4.1)	14.2

morphological differences: first, in cases of isthmic spondylolysis when the vertebra starts to slide forward (spondylolisthesis) the compensating mechanism of the lumbar spine is to increase the LA by increasing the wedging of the intervertebral disk above the slipped vertebra. This mechanism of increasing the lordotic wedging above the slipped vertebra helps to maintain the line of gravity close to the biacetabular line; second, this morphology might suggest that in cases of isthmic spondylolysis when the vertebra starts to slide forward (spondylolisthesis) it is also rotating around its coronal axis—the anterior wall of the vertebral bodies is rotating downwards in relation to the posterior wall. As a result, the wedging of the disc above the slipped vertebra is increased and the wedging of the disc below is decreased. This, in turn, will affect the biomechanical properties of the discs involved and their ability to withstand loads [24–26].

The morphology of the spine of individuals with isthmic spondylolisthesis compare to that of degenerative spondylolisthesis reveals some similarities and some distinct differences. The major similarity is in the high lordotic wedging of the L5 body. In both groups, the vertebral body at L5 is 3–4° more lordotic than in normal individuals. The major differences are in the ΣB and in the segmental intervertebral disk wedging. Individuals with isthmic spondylolisthesis show normal ΣB wedging and very lordotic wedging of the intervertebral disk above the slipped vertebra. Individuals with degenerative spondylolisthesis show ΣB wedging that is 10° higher than the normal and small disk wedging at L5–S1. The small intervertebral discs of the degenerative spondylolisthesis group might be a predisposing factor to the development of degenerative spondylolisthesis or a compensatory mechanism to the ventral slippage of the vertebra. Future study using a longitudinal design might answer this question.

Intervertebral disc wedging is one of the indicators of lumbar intersegmental instability [11]. The differences between the wedging of the intervertebral discs in isthmic spondylolisthesis—high disc wedging above the slipped vertebra—to that of degenerative spondylolisthesis—low disc wedging above and below the slipped vertebra—indicate two different patterns of morphological changes in the disc.

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Conflict of interest None of the authors have any conflict of interest regarding the contents of this article.

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